ExOne Company (formerly Extrude Hone Corporation)

3D Printing Process to Improve Lost-Foam Castings

In the late1990s, the U.S. auto industry widely replaced steel engine components with aluminum cast components to reduce weight and energy consumption. These components, such as cylinder heads, were difficult to cast because of their complex internal air, exhaust, and cooling passages. The most efficient process for producing intricate cast aluminum parts was called lost-foam casting (LFC). However, the processes used to design and manufacture the tools to produce the foam patterns were inflexible, costly, and time consuming.

Extrude Hone Corporation formed a joint-venture partnership with General Motors (GM) Powertrain Group and subcontractor Massachusetts Institute of Technology (MIT) to develop technologies to repeatedly print bonding material onto paper-thin layers of powder to build up a part shape from a computer-aided design (CAD) model. In this manner, they would construct metal prototypes and LFC tooling (molds) directly from the CAD model in a process called three-dimensional printing (3DP). If successful, 3DP could produce complex geometrical configurations in a single component and replace numerous assembled components containing intricate contours and passages.

3DP technology had high technical risks: making the larger component sizes required completely redesigning MIT's existing 3DP machine; larger tools meant overcoming increased part distortion; and using LFC and 3DP for mass-manufactured auto components required low-cost, large-scale volumes and quick turnarounds. For these reasons, the joint venture was unable to obtain conventional financing and applied to the Advanced Technology Program (ATP) for cost-shared funding.

ATP approved funding for a four-year project as part of a 1997 focused program, "Motor Vehicle Manufacturing Technology"; a one-year, no-cost extension was later granted due to the project's technical difficulties. Extrude Hone achieved nearly all of its technical goals and received public attention in numerous publications. GM shifted its priorities away from LFC at the end of the project. Extrude Hone and MIT applied for five patents for innovations associated with the ATP-funded technology. In 2005, it spun off an internal research department called ExOne as a separate development company. ExOne has sold approximately 60 3DP machines in various models to major manufacturers in prototype development and tooling production. They also produce prototypes and tooling as a service for smaller manufacturers. This technology forms ExOne's core business, which had grown from 6 employees at 1 location in 1997 to 80 employees at 5 locations by March 2006.

COMPOSITE PERFORMANCE SCORE
(based on a four star rating)
* * * *

Research and data for Status Report 97-02-0055 were collected during February – March 2006.

Lost-Foam Casting Requires Long Lead Times and Expensive Tooling

The auto industry has been under continual pressure to reduce weight and energy consumption, while at the same time controlling costs. This pressure sparked a trend to move from iron and steel to aluminum components. The process of making and assembling cores and molds for casting components limited the design opportunities available with conventional sand-mold methods. Cylinder heads are especially difficult to cast because of their complex internal air, exhaust, and cooling passages.

The lost-foam casting (LFC) process, patented in 1958, was the most cost-effective method of manufacturing cast cylinder heads with the complex geometry required for the high power-density, lightweight engines. LFC starts with tiny beads, usually polystyrene, that contain pentane as a blowing agent. The beads are blown into a mold to form pattern sections. A steam cycle expands and fuses them, followed by a cooling cycle. The most costly step in the process is manually drilling and finishing several hundred holes, each 1/2 to 1/8 inches in diameter, into the tool, to allow the steam to make contact with the foam. Lost-foam patterns are created from slices of the final part, and the slices are glued together with hot-melt glue to create a complete component. A gating system to pour hot liquid metal into the pattern is similarly attached with hot-melt glue. Next, the foam cluster is dipped in a slurry to form a ceramic coating for insulation. After the coating dries, the foam cluster is placed into a flask and packed with bonded sand. The ceramic coating forms a barrier to keep molten metal from penetrating or eroding the sand. The coating helps protect the structural integrity of the casting as well. Molten aluminum is poured into the foam pattern, vaporizing the polystyrene and replacing it to form its exact shape. The aluminum must be hot enough to fill the mold and melt the foam throughout the form before it solidifies, with no bumps, seams, or parting lines.

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The LFC process allows complex and detailed passages and other features to be cast directly into the cylinder block, such as oil galleries, crank case ventilation channels, oil drain back passages, and coolant passages. These features would otherwise require drilling or external plumbing, which could cause leaks. LFCs had tighter dimensional tolerances than previous sand castings, because the process eliminates variations caused by core shift and core variability. Furthermore, LFCs cause much less wear over the production life of the tool (or mold). As a result, LFC provided greater accuracy, significantly lower machining costs and infrastructure investment, and fewer opportunities for errors in machining and assembly.

However, the lead times for designing and manufacturing the tools (molds) to form the foam patterns were substantial, and changes were difficult to incorporate. In 1997, LFC tooling required more than 50 components configured in a complex assembly because of numerous connections for pellet insertion, steam, and moisture vacuum. In addition, LFC could not produce geometrical configurations such as undercuts and contoured internal passages.

Extrude Hone Proposes Three-Dimensional Printing

Extrude Hone Corporation was a small, innovative company that built machine tools. They formed a joint venture with General Motors (GM) Powertrain Group, a major auto manufacturer, to reduce by 50 percent the time to produce LFC tooling.

The joint venture proposed to combine LFC with three-dimensional printing (3DP), a process developed and patented by the Massachusetts Institute of Technology (MIT), which would be a subcontractor on the project. 3DP would eliminate the machining of the mold contours and the manual process of drilling and finishing steam holes. The approach would consist of repeatedly printing thin layers of bonding material onto a thin layer of powder to build up a tool shape from a computer-aided design (CAD) model.

Extrude Hone would lead in scaling up the printing process, furnace processing, and integration of a control system. GM had been using LFC since 1982 and would lead component design, database management to develop improved CAD models, and initial tooling manufacture. GM had brought lost-foam tooling in-house in 1996 and had eventually reduced the LFC cycle time from 32 to 6.5 weeks. MIT would provide 3DP technology and would develop the base material (composite metals) to produce a fully porous tool that would allow steam entry. MIT would also design a multiple-nozzle print head for large-scale printing of the bonding material.

The focus of this project was to develop an alternate method for making LFC tooling. The joint venture partners would construct LFC tooling with precisely formed mold contours and a porous surface that allowed steam to pass through, which would eliminate the need to machine contours and drill steam holes. MIT had invented this 3DP "rapid prototyping" technology in 1989 and had patented it in 1993. The 3DP machine builds up complex shapes layer by layer, based on a computer file that can depict the object as a series of horizontal slices (see Figure 1).

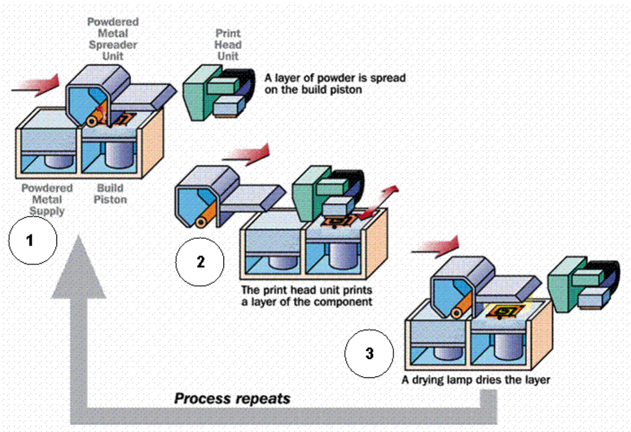

Figure 1. The 3DP process: 1) the powdered metal supply delivery piston pushes up a layer of powder, which is spread onto the top surface of the object to be created (on the build piston); 2) the print head sprays a layer of liquid adhesive on the powder to bind it according to the CAD design; 3) a drying lamp dries the layer, and the fabrication piston moves the object down one layer. The process repeats, adding layers until the object is completely "printed." When the object is removed from the build cylinder, the loose powder falls away. The result is a "green" object that is ready for firing.

Combining LFC and 3DP would change the tooling design and manufacturing paradigm. Complex geometrical configurations could be produced in a single component that could replace numerous assembled components that had complex contours and passages. Such a process could simplify the production of vehicle parts, as well as improve their quality. The result might save money and produce superior vehicles. In addition, the process could potentially generate geometrical configurations such as porous or foam-like surfaces that were impossible to create by other means. A porous surface would eliminate the need to manually drill hundreds of steam holes. The Extrude Hone joint venture proposed to build a prototype set of molds and multiple sets of production tooling so that the large castings required by the auto industry could be mass produced.

However, taking LFC and 3DP technology to a higher level had the following high technical risks:

- Larger engine components would require a complete redesign and reconfiguration of MIT's 3DP machine.
- Larger molds would increase part distortion, which would have to be overcome to maintain precise measurement.
- Applying LFC and 3DP to mass-produced automotive components would require reducing cost, scaling up volumes, and meeting quick turnaround requirements.

Combining LFC and 3DP could consolidate many components into one, improve flow design of complex passages, and provide the ability to design and produce with greater flexibility and innovation. As a result, the companies could produce better engineered engine components in fewer steps and shorter time.

The high technical risks made it impossible for the Extrude Hone joint venture to obtain commercial funding. Therefore, the company applied for and received cost-shared funding in 1997 from ATP for a four-year project under the "Motor Vehicle Manufacturing Technology" focused program. The project was later extended by one year at no additional cost when the project encountered technical difficulties.

Extrude Hone Performs Three Primary Tasks

The goal of the project was to supply automated LFC tooling to GM and other manufacturers for a wide class of engine components. In order to achieve success, the project researchers identified three primary tasks. For task one, developing the 3DP/LFC process, researchers would investigate LFC materials and options for creating the skeleton and reducing its porosity. They would apply 3DP technology to manufacturing LFC tooling and would establish precise measurements for forming tools of different sizes. Finally, they would design, manufacture, test, and improve specific components developed by GM.

For task two, designing and building the machine cell or model, GM would introduce features to the 3DP machine that could address scale-up, new materials, and new geometries. The project also required a large scaled-up furnace with uniform temperature throughout the furnace's "hot zone," peak temperature capability, atmosphere control, and larger overall usable volume. The joint venture would design and build two 3DP prototype machines capable of manufacturing lost-foam cores to produce automotive engine castings. GM would work closely with Extrude Hone to implement the PC-based control systems in the prototype machines. The control system would include video and data links to permit high-speed process data interchange for part model data input, process setup, and remote process monitoring and diagnosis.

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For task three, validating and demonstrating the 3DP/LFC process, they would establish a pilot operation by installing a prototype machine at GM's Casting Advanced Development Lab in Saginaw, MI. GM would send actual production engine component design models to Extrude Hone, which would simulate a real-world production cycle by acting as a tier one tooling supplier. After a successful simulation, Extrude Hone would demonstrate production tooling to GM personnel, tier one suppliers, other auto supply chain vendors, and the "Big Three" auto companies. They would make the pilot available to these companies to test similar applications. The challenge was to reduce the time between completed design and produced parts from six and a half weeks to two. Researchers expected $20 million in savings in the cycle from design to full-volume production. They also expected that more design iterations would reduce production times further and improve engine design and performance.

The joint venture team had specific objectives to meet production goals:

- Eliminate steam holes for venting in the tooling process to save cost and time.
- Print a tool component in an eight-hour shift.
- Scale up the machine for larger tool components.
- Meet tolerance specifications at critical areas where tooling components meet. The goal was to decrease shrinkage from the expected 1.7 percent to less than 0.1 percent.
- Increase the overall speed of LFC tool processing development speed by a factor of 10 or more.

The major obstacle to achieving greater speed in LFC tool processing lay in printing. Existing print head technology was a modular design of eight nozzles. The goal was to scale up to 96 nozzles and maintain accurate control of the print jets. The eight-nozzle ink jet print head required four pumps. Using existing technology, a 96-jet print head would require 48 pumps, which was not practical.

Joint Venture Makes Progress toward Goals

Developing automated LFC technology proved more difficult than anticipated. As a result, the joint venture needed a one-year, no-cost extension to complete its development. Nevertheless, Extrude Hone and its partners made significant strides:

- **Bigger and Better Tooling.** By June 1999, Extrude Hone had printed its first foam tools and had presented half-scale prototypes to GM. The tools measured about 10.5 x 10.5 x 2 inches, some of the largest 3DP-metal tools of the time. Each print run required 30 hours on one of Extrude Hone's prototype RTS-300 3DP machines. The company also printed test bars measuring 1 x 0.5 x 0.5 inches to analyze surface roughness during and after firing and finishing. The test bars demonstrated a reduced amount of roughness and less total surface profile variation (more uniform surface). Researchers reduced total surface profile variation from 251.8 micrometers (µm) to 107.4 µm (that is, a close-up view of the surface would show the maximum variation from the highest point to the lowest was 107.4 µm) and reduced surface roughness from 18.7 µm to 15.7 µm.
- **Steam Vents.** MIT developed a process using 3DP to locally deposit an "infiltration stop" material in various locations within a metal component. These stops would automatically leave ventilation holes in the printing process to expand and fuse the foam

pellets. The material was leached out, leaving a porous region.

- **Faster, More Reliable Processing.** Extrude Hone developed a binder to improve performance, resulting in parts that were less susceptible to distortion during thermal processing. The binder allowed tools to harden while still in the print box supported by loose powder, which reduced the likelihood of damage during handling in the fragile "green" state. The binder also allowed a single-step firing cycle by eliminating a second 12- to 20-hour cycle.

By 2000, GM had molded 65 foams in the prototype lost-foam machine and had made castings. Completing a tool required about 110 hours of development time; although this was still slow compared to milling, it was a good start. The next goal was to shorten development time to 43 hours by relying on improved automation to reduce labor requirements. Following that, the next steps were to reduce warping, improve accuracy, and include the steam vents.

By the end of the ATP-funded project in December 2002, Extrude Hone had produced a prototype R10 3DP machine (see Figure 2), which automatically included 30,000 normal-sized steam holes in a component. Thus the steam process for expanding and fusing foam pellets was more precise and consistent. A cylinder head still required 10 tools: 5 pairs to produce the 5 foam casts, which would be glued together. Although MIT did not reach the target 96-nozzle print head, they produced a print head with 32 nozzles that performed adequately. Extrude Hone also made the largest rapid prototype six-cylinder head that had ever been created.

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The company's next goals were to scale up this technology to efficiently print larger numbers of small parts at low cost. New application areas could include manufacturing molds for plastic injection molding, and door hinges, as well as replacing obsolete parts that the Department of Defense could no longer obtain from original manufacturers. Extrude Hone later completed a successful project with the Department of the Navy to produce large and small metal parts.

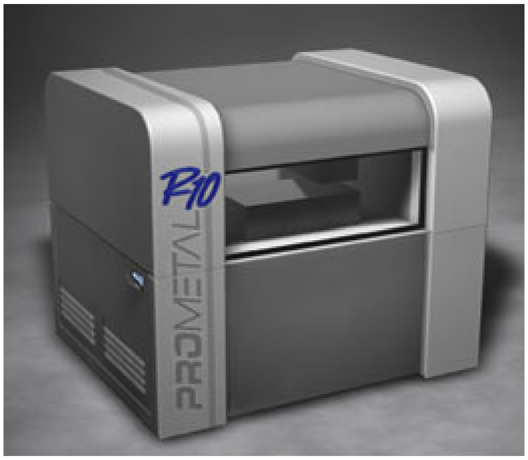

Figure 2. Extrude Hone's R10 machine, a direct outgrowth of the ATP-funded 3DP technology. The first commercial installation was in 2004. Prototypes produced by the R10 were three to four times less expensive than those produced by the previous machine. Accuracy also improved. A new binder system allowed Extrude Hone to handle large parts (up to 39 x 20 x 10 inches) without distortion.

3DP Technology Achieves Commercial Success

Extrude Hone and MIT continued to develop the LFC/3DP technology after the ATP-funded project ended in 2002, but GM changed its priorities and ended its involvement in the project. According to Mike Rynerson, an engineer on the project, Extrude Hone would not be in the business of rapid casting if not for ATP support. This technology grew to represent 50 percent of the company's business.

In addition to producing molds, Extrude Hone uses 3DP technology to build metal parts directly, called rapid casting. The company produces metal prototype parts and tools in stainless steel, tungsten, and tungsten carbide. Printed parts are fired for strength and then may be infiltrated with low-melting-point alloys to produce fully dense parts. This new process eliminates the need to machine intricate molding contours, as well as the labor-intensive process of drilling and finishing holes using the LFC process. The 3DP process is adaptable to a variety of materials, allowing the production of metallic and ceramic parts with new compositions. Extrude Hone's commercial processes include:

- Direct production of tooling for injection molding
- Direct production of metal prototypes and end-use parts
- Improved rate and dimensional control for injection-molded parts

Building on the ATP-funded technology, Extrude Hone developed two 3DP systems, the S15 and SR-2 (see Figure 3). These systems produce tooling with integral cooling passages in complex patterns. Tools with integral cooling passages can control temperature accurately and yield reproducible parts with predictable properties. Channels can also be printed in a variety of sizes and patterns.

Figure 3. Extrude Hone's S15 and SR-2 systems. The build envelope (chamber that determines component size) of the S15, introduced in 2001, is by far the biggest in the industry at 59 x 30 x 28 inches. The SR-2, introduced in 2005, handles components up to 8 x 10 x 8 inches. These two 3DP machines were iterations of the original ATP-funded 3DP technology.

Extrude Hone's business grew with its technical success. By 2003, the company had expanded to 20 locations globally and more than 400 employees. Extrude Hone consistently invests 10 to 15 percent of its annual revenues into research and development. In early 2005, as Kennametal Corporation was acquiring the company, Extrude Hone CEO Larry Rhoades formed ExOne and spun off the 3DP business to it. This allowed Extrude Hone's former owners to retain the 3DP business. As of 2006, ExOne is scaling up the technology for larger, faster machines to produce bigger components. At the same time ExOne is scaling up the level of detail to produce smaller, more accurate components.

New Applications for 3DP

Extrude Hone applied the results of this project to other areas, using the same equipment. For example, an aerospace firm required prototypes of a thrust reverser. Normally, producing this prototype would require extensive manual labor. Extrude Hone made accurate half-scale parts for testing in a wind tunnel. The part was assembled into a jet engine on an aircraft and flown successfully. Total development time from CAD to parts delivery was about four weeks.

MIT also developed new applications for 3DP technology, relying on advances from the ATP-funded project:

- Gradient Index (GRIN) Lenses offer an alternative to the painstaking craft of polishing curvatures onto glass lenses. By gradually varying the index of refraction within the lens material, light rays can be smoothly and continually redirected toward a point of focus. The internal structure of this index gradient reduces the need for tightly controlled surface curvatures and results in simple, compact lens geometry. MIT used 3DP to fabricate GRIN lenses in work sponsored by the Defense Advanced Research Projects Agency.
- MIT aimed to use 3DP to directly produce hollow metal parts greater than 0.5 m. They focused on structural parts with complex internal geometry, including truss structures, ribs, and the like. This work was sponsored by the Office of Naval Research.
- MIT intended to apply 3DP to produce tungsten carbide/cobalt cutting inserts (blades). This fabrication method offers increased flexibility in geometry, in composition, and in response to market demand over the existing practice of dry pressing. This project was sponsored by Kennametal Corporation and Valenite Corporation.

As of 2006, MIT had licensed the 3DP technology to three companies in spillover applications to other production areas.

Therics Inc. produces time-release drug-delivery devices. A multiple-jet print head prints a substrate that releases several drugs into the bloodstream. 3DP enables complex drug-release profiles, precise dosage control, and rapid formulation without waste. The ability to control the deposition of multiple drugs and the level of porosity are important. Therics is designing applications of antihistamine and anti-inflammatory medications.

Z Corporation uses 3DP to build the world's fastest 3D models of prototype products. "With the Z Corp. System, we can have a discussion in the morning, make a suggestion, break for lunch and see the results in early afternoon. No other tool can do this," said Mike Jahnke of Motorola. They have licensed the 3DP technology for concept modeling. Similar to ExOne's system, Z Corporation's Z402 system prints a water-based liquid onto layers of starch powder, using a multiple-nozzle print head.

The Timberland Company was hiring professional model makers to turn 2D CAD footwear drawings into 3D wood or foam prototypes. These prototypes typically took a week or more to create and cost $1,200 each. They turned to Z Corporation's Spectrum Z510 3DP printer, which accepts CAD files from Timberland. The prototype now requires 90 minutes and costs $35 (see Figure 4). This allows engineering and marketing employees to collaborate more often and more closely. Timberland's typical design cycle was shortened from three weeks to two. Toby Ringdahl, a CAD manager at Timberland, said, "In our industry, the pressure is always intense to quickly and affordably turn the marketer's vision and the consumer's taste into reality that performs well, feels good and looks great. Z Corp[oration] printers have done exactly that for us, compressing our design cycles, lowering our costs and helping us produce better products for our customers."

Figure 4. The Z Corporation Spectrum Z510 3DP printer produces multicolored, highly detailed prototypes such as this Timberland sole.

Aprecia Pharmaceuticals produces pharmaceuticals, dietary supplements, and cosmetics based on MIT's 3DP technology. Aprecia uses ink-jet printing with multiple print layers to build 3D constructs, precisely controlling the loading and spatial distribution of a drug, as well as dosage release.

Conclusion

Extrude Hone Corporation used a 1997 ATP-funded focused project in "Motor Vehicle Manufacturing Technology" to develop a key technology called lost-foam casting (LFC) with 3-dimensional printing (3DP). General Motors (GM) was a joint venture partner, and Massachusetts Institute of Technology (MIT) served as a subcontractor. The joint venture met most of its technical goals in developing LFC with 3DP. Extrude Hone and MIT received two patents (with three patents pending), and technology advances attracted attention through industry publications. GM did not pursue LFC/3DP technology after the ATP-funded project ended in 2002. ExOne, the research and development arm of Extrude Hone, continued developing LFC and 3DP after the ATP-funded project ended and was later spun off as a separate company in 2005. As of 2006, the company had provided 3DP services as well as three different 3DP machine models to customers for prototype and tooling production. MIT licensed its 3DP technology to three companies for various applications.

PROJECT HIGHLIGHTS
ExOne Company (formerly Extrude Hone Corporation)

Project Title: 3D Printing Process to Improve Lost-Foam Castings (Development of the 3D Printing [3DP] Process for Direct Fabrication of Automotive Tooling for Lost Foam Castings [LFC])

Project: To develop computer systems and three-dimensional printing (3DP) process technologies to automatically generate tasking to manufacture styrofoam patterns of complex engine components from a parts-design database, enabling lower cost production of aluminum engine components with complex shapes. The resulting technologies also could be adapted for the manufacture of turbine components and in the creation of new materials such as metal "foams."

Duration: 12/19/1997 - 12/18/2002
ATP Number: 97-02-0055

Funding (in thousands):

ATP Final Cost	$3,169	49.8%
Participant Final Cost	3,192	50.2%
Total	$6,361	

Accomplishments: Extrude Hone accomplished most of its technical goals during the ATP-funded project. Although General Motors (GM) left the joint venture at the end of the project in 2002, Massachusetts Institute of Technology (MIT) and Extrude Hone continued to collaborate through ExOne, the development arm of Extrude Hone, and achieved the following:

- **Bigger and Better Tools.** By June 1999, Extrude Hone had printed some of the largest 3DP-metal tools of the time, measuring approximately 10.5 x 10.5 x 2 inches. Each print run required 30 hours on one of Extrude Hone's prototype RTS-300 3DP machines. The company also printed test bars measuring 1 x 0.5 x 0.5 inches to analyze surface roughness during and after firing and finishing. Researchers reduced total surface profile height variation from 251.8 micrometers (µm) down to 107.4 µm and reduced surface roughness from 18.7 µm to 15.7 µm. Application and production involves the use of a wide range of materials including stainless steel, steel tungsten, and tungsten carbide.

- **Steam Vents.** MIT developed a process using 3DP to locally deposit an "infiltration stop" material (colloidal silica) in different locations within a metal component. These would automatically leave ventilation holes in the printing process in order to expand and fuse the foam pellets. The silica is later leached out with sodium hydroxide to leave a porous region behind. This process automatically produces approximately 30,000 regular-sized steam holes in a component. Hole sizes were reduced from 1/8 to 1/2 inches down to 0.014 inches. This made the steam process for expanding and fusing foam pellets more precise and consistent. Extrude Hone's MicroFlow AFM machines are capable of executing this process.

- **Faster, More Reliable Processing.** Extrude Hone developed a novel binder, which resulted in parts that were less susceptible to distortion during thermal processing. The new binder allowed tools to be hardened while still in the print box, supported by loose powder. This reduced the likelihood of damage during handling in the fragile "green" state. It also allowed a single-step firing cycle and eliminated a second 12- to 20-hour firing cycle. Development time, from receiving computer-aided design (CAD) data to actual part with minor machining needed, was reduced from 6.5 weeks to 2 to 3 days.

- **Prototype R10 3DP Machine.** By the end of the ATP-funded project in December 2002, Extrude Hone had produced a prototype R10 3DP machine. Accuracy increased and cost was reduced by a factor of three to four. A cylinder head still required 10 tools: 5 pairs to produce the necessary 5 foam casts. These were glued together to form the cylinder head. The largest pieces were 39 x 197 x 4 inches, the largest ever produced at that time. Although MIT did not reach the target 96-nozzle print head, they were able to produce a print head with 32 nozzles, which performed adequately. Extrude Hone also made the largest rapid prototype six-cylinder head that had ever been created.

The ATP-funded technology was awarded two patents, with three additional patents pending:

- "Three dimensional printing methods"
(No. 6,146,567: filed September 14, 1998, granted November 14, 2000)

- "Method for article fabrication using carbohydrate binder"
(No. 6,585,930: filed April 25, 2001, granted July 1, 2003)

PROJECT HIGHLIGHTS
ExOne Company (formerly Extrude Hone Corporation)

Commercialization Status: As a result of Extrude Hone's technical and business growth, the company spun off its research and development arm, ExOne, in 2005. ExOne offers rapid prototyping and tooling production services to manufacturers and sells 3DP machines for two key processes: direct metal printing and rapid casting.

ExOne offers three commercial 3DP machines based on the ATP-funded technology:

- **R10.** Extrude Hone still sells the R10 3DP machine, which was the original prototype designed during the ATP-funded project. It is able to produce tools up to 39 x 197 x 4 inches.
- **SR-2.** This system is built for speed, agility, and flexibility to rapidly fabricate sand-cast molds and cores. It enables on-demand casting of aluminum alloys, copper alloys, iron, and magnesium. It can produce tools up to 8 x 10 x 8 inches. Users can print a CAD model one day and cast the next, with no pattern.
- **RCT S15.** This system is an extremely flexible implementation of the 3DP rapid-casting technology (to produce prototype metal parts for testing). This factory-floor solution provides everything necessary to produce casting molds and cores directly from CAD files. Each S15 system includes a process station and an unloading station. These two components are connected by a conveyor to allow easy transfer of molds from the printing station to the unloading station. The system also includes a mixing unit that prepares and stages sand for use during the process. The S15 has the largest manufacturing size in the industry (up to 59 x 30 x 28 inches) and is the only system using foundry-grade materials.

These 3DP machines are used to perform the following two processes:

- **Direct Metal Printing.** ExOne offers cutting-edge rapid manufacturing capability. The 3DP process produces fully functional metal workpieces directly from CAD files in a matter of days rather than weeks or months. The 3DP process prints a workpiece one layer at a time from metal powder. Among the benefits are virtually unlimited design flexibility, complex internal geometries, undercuts, angled passages, and the opportunity to create countless other component features that would be impossible to duplicate with traditional machining methods.
- **Rapid Casting.** Using the same technology from the direct metal process, rapid casting produces sand-casting molds and cores directly from a CAD model, enabling the fabrication of molds and cores that are often impossible to create by conventional means. This offers the flexibility to produce complex, finely detailed, patternless castings while reducing production costs and time to market.

Outlook: The outlook for ExOne's 3DP rapid-casting technology is strong. The company has sold approximately 60 3DP units. Manufacturers buy these machines and use them for rapid prototyping and direct metal printing. In addition, ExOne provides these services to smaller companies on a piece-by-piece basis, when the company's volume cannot justify the cost of buying a 3DP machine (machines cost up to $1.5 million). ExOne is in the process of scaling the technology to larger, faster machines. At the same time the company is scaling down sizes to facilitate smaller, more accurate manufacturing.

Composite Performance Score: * * * *

Number of Employees: 6 employees at project start, 40 as of December 2002 (project end), 80 as of March 2006 (ExOne, a spin-off from Extrude Hone)

Focused Program: Motor Vehicle Manufacturing Technology, 1997

Company:
The ExOne Company (formerly Extrude Hone Corporation)
8011 Pennsylvania Ave.
Irwin, PA 15642

Contact: Ralph L. Resnick / Mike Rynerson
Phone: (724) 863-9663

Company:
General Motors Powertrain Group
895 Joslyn Ave.
Pontiac, MI 48340-2920

Contact: William Swanteck, Terry McCarthy
Phone: (313) 323-2101

Subcontractor:

- Massachusetts Institute of Technology
  Department of Mechanical Engineering
  Cambridge, MA

PROJECT HIGHLIGHTS
ExOne Company (formerly Extrude Hone Corporation)

Publications: Extrude Hone and MIT researchers disseminated their findings and received significant public attention through the following publications:

- Bylinsky, Gene. “Industry’s Amazing New Instant Prototypes: Turning Computerized Designs into Solid Objects—even Salable Products—Takes Just the Push of a Button.” *Fortune*, p. 120, January 12, 1998.

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- Chilukuri, Ram. “Design and Fabrication of a Post-Processing Furnace for 3D Printed Parts.” Thesis (S.M.), Massachusetts Institute of Technology, Dept. of Mechanical Engineering, 2000.

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